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Root growth and water uptake in winter wheat under deficit irrigation

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Abstract

Root growth is critical for crops to use soil water under water-limited conditions. A field study was conducted to investigate the effect of available soil water on root and shoot growth, and root water uptake in winter wheat (*Triticum aestivum* L.) under deficit irrigation in a semi-arid environment. Treatments consisted of rainfed, deficit irrigation at different developmental stages, and adequate irrigation. The rainfed plots had the lowest shoot dry weight because available soil water decreased rapidly from booting to late grain filling. For the deficit-irrigation treatments, crops that received irrigation at jointing and booting had higher shoot dry weight than those that received irrigation at anthesis and middle grain filling. Rapid root growth occurred in both rainfed and irrigated crops from floral initiation to anthesis, and maximum rooting depth occurred by booting. Root length density and dry weight decreased after anthesis. From floral initiation to booting, root length density and growth rate were higher in rainfed than in irrigated crops. However, root length density and growth rate were lower in rainfed than in irrigated crops from booting to anthesis. As a result, the difference in root length density between rainfed and irrigated treatments was small during grain filling. The root growth and water use below 1.4 m were limited by a caliche (45% $CaCO_3$) layer at about 1.4 m profile. The mean water uptake rate decreased as available soil water decreased. During grain filling, root water uptake was higher from the irrigated crops than from the rainfed. Irrigation from jointing to anthesis increased seasonal evapotranspiration, grain yield, harvest index and water-use efficiency based on yield (WUE), but did not affect water-use efficiency based on aboveground biomass. There was no significant difference in WUE among irrigation treatments except one-irrigation at middle grain filling. Due to a relatively deep root system in rainfed crops, the higher grain yield and WUE in irrigated crops compared to rainfed crops was not a result of rooting depth or root length density, but increased harvest index, and higher water uptake rate during grain filling.

Introduction

Winter wheat (*Triticum aestivum* L.) is a major crop in the Southern High Plains of USA and is grown under both rainfed and irrigated conditions (Howell et al., 1995; Musick and Dusek, 1980a; Winter and Musick, 1993). In this region, grain yield and water-use efficiency of rainfed wheat are mainly limited by soil water deficit during spring growth through grain filling due to a high-evaporative-demand (Howell et al., 1997) and highly variable seasonal precipitation (Musick and Dusek, 1980a). In Texas High Plains, rainfed winter wheat yield ranged from 0 to 2.5 Mg ha^{-1}, while water use-efficiency based on grain yield (WUE) ranged from 0 to 8 kg ha^{-1} mm^{-1} (Jones and Popham, 1997; Musick et al., 1994). For irrigated wheat, yield was in the range of 3 – 8 Mg ha^{-1}, while WUE was in the range of 5 – 12 kg ha^{-1} mm^{-1}

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(Eck, 1988; Howell et al., 1995; Musick et al., 1994). Because of declining groundwater resources, deficit irrigation has been widely practiced in the region for winter wheat management (Eck, 1988; Musick et al., 1994). Deficit irrigation is the application of less water than is required for potential evapotranspiration (ET) and maximum yield, resulting in conservation of limited irrigation water (Musick et al., 1994). Deficit irrigation of wheat is also practiced in other regions in the world (Oweis et al., 2000; Zhang et al., 1998). Studies showed that deficit irrigation significantly increased grain yield, ET and WUE as compared to rainfed wheat (Eck, 1988; Oweis et al., 2000; Schneider et al., 1969).

Water management under deficit irrigation focuses on efficient use of limited soil water and increasing crop water-use efficiency (Musick et al., 1994; Zhang et al., 1998). Root growth is critical for crops to use soil water and obtain high yield under water deficit conditions (Robertson et al., 1993). Johnson and Davis (1980) showed that the water extraction in plots with lower yield (0.84 Mg ha^{-1}) was limited to 0.9 m profile and left 72 mm available water in 2.1 m profile after harvest. In comparison, for the higher yield plots (2.3 Mg ha^{-1}), there was only 25 mm available soil water left in the 2.1 m profile after harvest because crops used more water from the deeper soil profile. Winter and Musick (1993) found that late planting (early November) significantly reduced plant rooting depth and grain yield as compared to early planting (middle August) and normal planting (early October). The depth of soil water extraction was only 1.2 m at anthesis in late planting, while the depth of soil water extraction was 2.4 m in normal planting. Although information is available on shoot growth, ET, yield response, and water-use efficiency under both rainfed and deficit irrigation conditions (Eck, 1988; Musick and Dusek, 1980a; Musick et al., 1984), little is known in root growth and its relations to water uptake in the area. The objectives of this study were to (1) investigate root and shoot growth, and root water uptake in winter wheat under a wide soil water availability regime from rainfed to adequate irrigation; and (2) test if rooting depth, root length density and root dry weight contribute to the increased grain yield and WUE in deficit irrigation treatments compared to rainfed.

Materials and methods

A field experiment was conducted at the US Department of Agriculture-Agricultural Research Service (USDA-ARS), Conservation and Production Research Laboratory at Bushland, Texas (Lat. 35° 11′ N, Long. 102° 06′ W; elevation 1170 m above mean sea level) during the 1992–1993 growing season on Pullman clay loam soil (fine, mixed, thermic Torrertic Paleustoll: USDA classification). The soil properties have been described by Taylor et al. (1963) and Unger and Pringle (1981). The winter wheat cultivar 'TAM 202' was planted on October 1, 1992 on a laser-leveled field with seeding rate of 70 kg ha^{-1} and a row spacing of 0.25 m. The field had been fallowed after wheat for about 15 months and all plots were fertilized with N (140 kg ha^{-1}) and P (40 kg ha^{-1}) a week before planting. Prior to planting, all the plots received a small irrigation (about 25 mm) for seed zone wetting to achieve uniform emergence. Plots were bordered with earth berms after planting. The experimental design was a completely random design with six replications, and plot size was 23.5 m by 11.0 m.

Irrigation treatments involved planned soil water deficit and irrigation application relative to plant development stage. The developmental stages were documented using Zadoks scale (Zadoks et al., 1974). There were eight irrigation treatments that ranged from rainfed (T-1), deficit irrigation (T-2 to T-7), to adequate irrigation (T-8) (Table 1). Four treatments (T-2, T3, T4 and T-5) received one-irrigation at jointing (100 mm on DOY 97, T-2), booting (100 mm on DOY 113, T-3), anthesis (140 mm on DOY 134, T-4), and middle grain filling (140 mm on DOY 146, T-5), respectively. Two treatments received two irrigations in total of 220 mm at jointing and anthesis (T-6), and at booting and middle grain filling (T-7). The adequate-irrigation treatment (T-8) received three irrigations in total of 300 mm at jointing, booting and anthesis (Table 1). Irrigation water was applied at once during the specific developmental stage by gated pipe, using flood irrigation that resulted in uniform plot coverage. The amount of water was measured using propeller-type meters (Musick and Dusek, 1980a; Musick et al., 1984).

The soil water content was measured using a 503 DR neutron probe (CPN International, Inc., Martinez, California) in all six replications from an access tube installed at the center of each plot. The measurements were made before planting, and then at 7 – 10 day intervals from the beginning of spring growth (end

Table 1. Irrigation scheduling and the amount of water application (mm) at different treatments (TRT)

TRT	First jointing	Booting	Anthesis	Grain filling	Total irrigation	Irrigation + precipitation
	DOY 97 7-Apr	DOY 113 23-Apr	DOY 134 14-May	DOY 146 26-May	mm	mm
T-1	Rainfed				0	254
T-2	100				100	354
T-3		100			100	354
T-4			140		140	394
T-5				140	140	394
T-6	100		120		220	474
T-7		100		120	220	474
T-8	100	100	100		300	554

winter dormancy) to physiological maturity (Zadoks 90). Readings were obtained by 0.2 m depth increment to 2.4 m in the soil profile. Volumetric soil water content was obtained by using calibration equations developed by Evett et al. (1993). Crop seasonal evapotranspiration was determined by summing precipitation, applied irrigation water, and the difference in soil water content between planting and maturity (Eck, 1988; Evett et al., 1993). Plant available soil water content was calculated based on current soil water content, upper (−0.03 MPa) and lower limits (−1.5 MPa) of soil water content (Sadras and Milroy, 1996). The values of soil water content at upper limit (−0.03 MPa) and lower limit (−1.5 MPa) in different soil layers were from Taylor et al. (1963). Shoot dry matter from all six replications was sampled as two paired rows per plot, 1 m length by 0.25 m spacing (0.5 m^2) with plants cut above the crown slightly below the soil surface. The sampling started 2 days prior to the first irrigation and continued at bi-weekly intervals until anthesis, then at weekly interval until physiological maturity (Zadoks 90). Shoot dry weight was determined after oven drying at 60 °C to constant weight. After maturity, grain yields were determined from duplicate plot combine samples of about 9 m^2 in each plot. Grain moisture content was determined by oven drying and yields and seed weight were reported as 12.5% moisture basis. Harvest index was calculated by the ratio of grain yield to final aboveground biomass. The final biomass was obtained using the average of shoot dry weight at last two sampling dates. Water-use efficiency in grain yield (WUE) and biomass (WUEbm) was determined by the ratio of grain yield or final biomass to seasonal ET (Musick et al., 1994; Stewart and Steiner, 1990).

Root samples from three replicates were taken at the beginning of spring growth (end of dormancy, DOY 55), floral initiation (between double ridge and terminal spikelet, DOY 85), booting (Zadoks 41, DOY 111), anthesis (Zadoks 61–65, DOY 131), and late grain filling (Zadoks 80, DOY 152) in treatments T-1, T-2, T-3 and T-8. At late grain filling (DOY 155), samples were also taken from the other four treatments (T-4, T-5, T-6 and T-7). The samples were taken from soil cores (53 mm diameter) by 0.05 m increment to 0.3 m, by 0.1 m increment to 1.0 m, and by 0.2 m increment to 2.0 m. Two cores per plot were collected, one within the crop row and one midway between rows. The soil samples were washed and root samples were separated using a Gillison hydropneumatic elutriation system described by Smucker et al. (1982) (Gillison's Variety Fabrication, Inc., Benzonia, Michigan). The soil samples were treated with hydrochloric acid for clay dispersion before washing. For root samples near soil surface, debris were removed manually. The root length was measured by using random line intersection method (Newman, 1966) with each sample being counted three times. Root length density was expressed as root length per unit of soil volume. After the root length was measured, samples were oven-dried and root dry weight was determined. The mean root water uptake rate over a drying period was calculated as the difference in volumetric soil water content divided by mean root length density between two intervals based on Meyer et al. (1990) and Robertson et al. (1993).

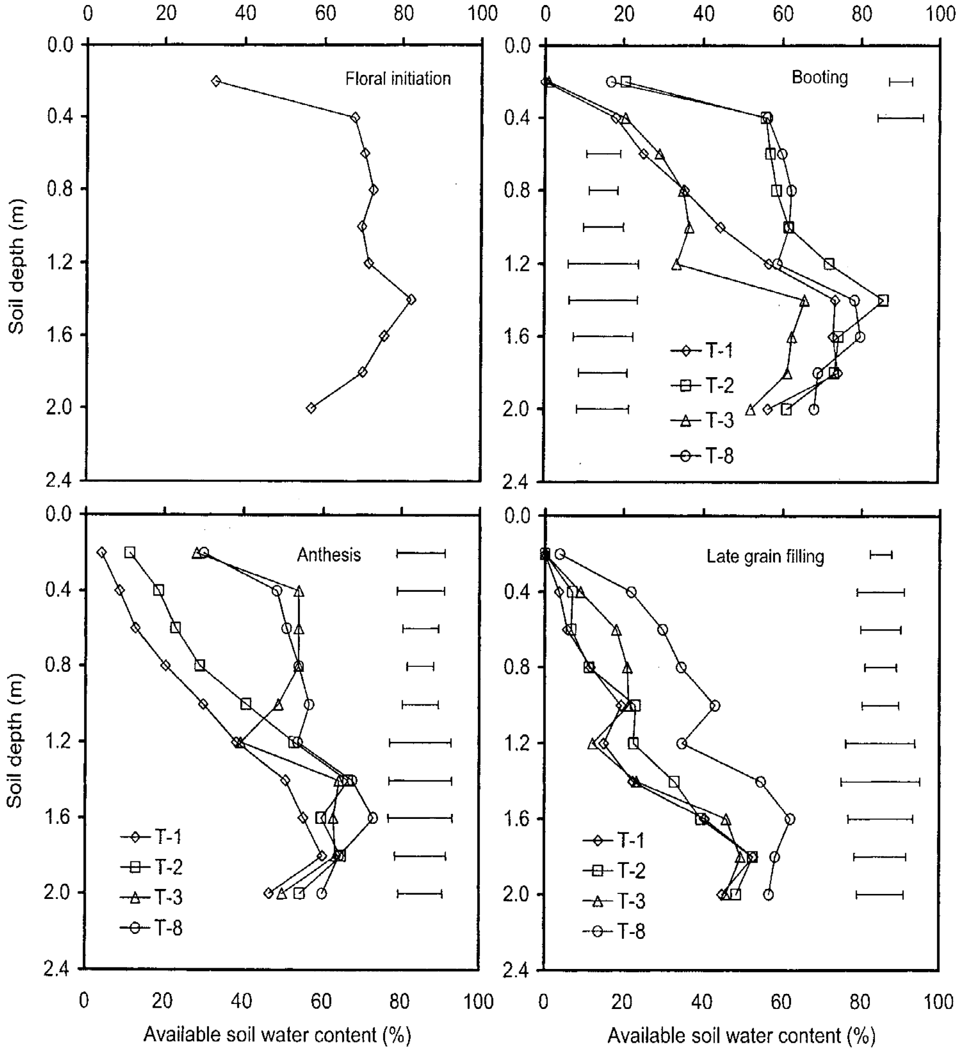

Figure 1. Plant available soil water in rainfed (T-1), two one-irrigation treatments (T-2 and T-3), and adequate irrigation treatment (T-8) over 2.0 m soil profile at floral initiation (DOY 83), 2 days before the irrigation at booting (DOY 111), 3 days before the irrigation at anthesis (DOY 131) and 7 days after the irrigation at grain filling (DOY 153). Horizontal bars represented the LSD at level of 0.05.

The SAS General Linear Model was used to analyze the main treatment effect and sampling date by treatment interaction in shoot and root variables and LSD was used to compare means among treatments (SAS Institute, Inc., 1989). Any significant difference was referred to the probability level less than 0.05.

Results and discussion

Temperature and precipitation

During the 1992–93 winter wheat growing season, the overall means of maximum and minimum temperatures were lower (16.7 and 0.9 °C) than long-term means (58 years) (18.4 and 1.8 °C) (Table 2). The lower monthly maximum and minimum temperatures than the long-term mean occurred in fall and winter months (November–February). The temperatures were close to long-term means during the active crop growth period (March–June) (Table 2). The monthly precipitation during winter (November through January) was higher than long-term mean. However, the precipitation was lower than average from early spring growing season to maturity except March (Table 2). The total growing season precipita-

Table 2. Summary of temperature and precipitation data during the 1992–93 winter wheat growing season at Bushland, Texas

Parameter	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Mean / Total
Temperature, °C										
Mean maximum	24.1	10.8	6.8	6.4	9.9	16.3	21.1	24.7	30.4	16.7
Long-term mean maximum	22.6	15.4	10.8	9.6	12.3	16.7	21.7	26.0	30.7	18.4
Mean minimum	5.1	–3.5	–6.5	–6.1	–5.7	–0.8	2.3	9.1	14.5	0.9
Long-term mean minimum	5.8	–0.9	–5.0	–6.5	–4.3	–1.1	4.1	9.5	14.8	1.8
Precipitation, mm										
Growing season sum	6	35	18	26	7	25	14	56	65	254
Long-term mean	39	18	15	13	13	19	28	67	75	287

tion was 254 mm in 1992–93 season, as compared to 287 mm for the long-term mean.

Plant available soil water

The plant available soil water contents over the 2.0 m profile in rainfed (T-1), treatments that received one-irrigation at jointing and booting (T-2 and T-3), and adequate irrigation treatment (T-8) are shown in Figure 1. At floral initiation (DOY 83), available soil water exceeded 60% except in the top layer (0–0.2 m) and 1.8–2.0 m layer. Because the irrigation treatments were not started on DOY 83, the average available soil water across all plots was presented. Available soil water declined to less than 40% over 0–1.0 m in T-1 and T-3 at booting (DOY 111), while available soil water in T-2 and T-8 was at similar level to that at floral initiation due to irrigation at jointing (DOY 97). At anthesis (DOY 131), available soil water was less than 30% in T-1 and less than 40% in T-2 over 0–1.0 m profile. However, the available soil water in the two treatments still exceeded 40% below 1.0 m. The T-3 and T-8 had higher available soil water than T-1 and T-2 (>40% over 0.2–2.0 m) due to irrigation at booting (DOY 113). At late grain filing (DOY 153), available soil water was less than 30% in T-1, T-2 and T-3 over 0–1.4 m, but was between 40 and 50% below 1.4 m. However, available soil water in T-8 was still between 30% and 60% over 0.6–2.0 m. The reduction of soil available water from floral initiation to late grain filling mainly occurred in the 0–1.4 m profile, the available soil water below 1.4 m reduced more slowly.

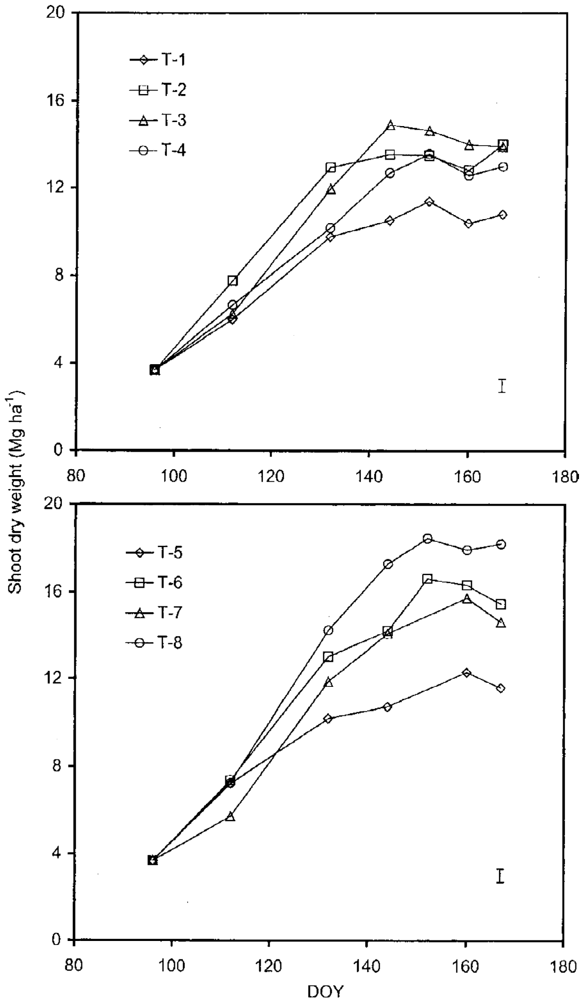

Figure 2. Crop shoot dry weight over the growing season from jointing to maturity in different treatments. Vertical bar represented the LSD at level of 0.05.

Shoot dry weight

Shoot dry weight for different treatments are shown in Figure 2. Depending on treatments, the maximum shoot dry weight was observed during middle to late grain filling. There were significant differences ($P < 0.01$) in shoot dry weight among treatments starting at booting, and the rainfed (T-1) had the lowest shoot dry weight. Irrigation application increased shoot growth and the fully irrigated wheat (T8) produced the highest shoot dry weight. These results are in agreement with findings from previous studies (Eck, 1988; Musick and Dusek, 1980a). The shoot dry weight among the deficit irrigation treatments (T-2 to T-7) was related to frequency and timing of irrigation application. Among the four one-irrigation treatments (T-2 to T-5), irrigation at jointing (T-2) and booting (T-3) increased shoot dry weight between jointing and anthesis, while irrigation at anthesis (T-4) increased shoot dry weight during grain filling. Crops in T-2 and T-3 had higher shoot dry weight at maturity than those in T-4 and T-5. Crops that received irrigation at middle grain filling (2 weeks after anthesis, T-5) had the same shoot dry weight as the rainfed treatment (T-1). The failure for increasing shoot dry weight by single irrigation at middle grain filling could be due to early senescence in rainfed treatment. The leaf area index in two days before irrigation was only 0.95 m^2 m^{-2} in rainfed treatment. For the two-irrigation treatments (T-6 and T-7), crops in T-6 had higher shoot dry weight than those in T-7 between booting and anthesis, but the two treatments had the same shoot dry weight during grain filling.

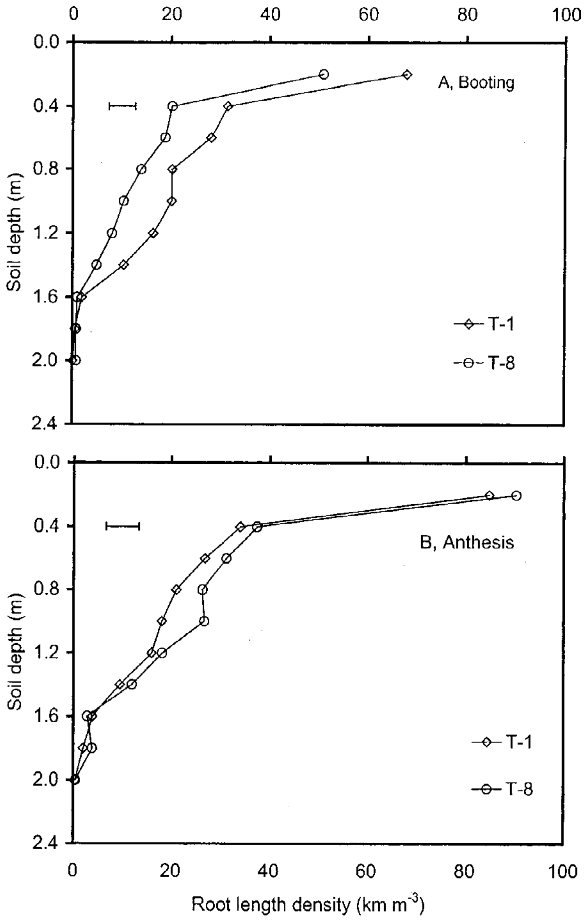

Figure 3. Root length density in rainfed (T-1) and adequate irrigation (T-8) at different layers of soil profile at booting (A) and anthesis (B). The horizontal bar represented the LSD at level of 0.05.

Root growth and water uptake

The root system at the first sampling date (DOY 55) extended to 1.4 m layer (data not shown). This depth was similar to the depth of soil water uptake (1.2–1.5 m) at the start of spring growth (DOY 66) in normal planting treatment (early October) as reported by Winter and Musick (1993). The depth of root system continued to increase to 2.0 m at booting (Figure 3A). Root length density decreased with depth. However, the root growth primarily limited to the 0–1.4 m profile based on the root length density distribution. The root length density below 1.4 m was 60–99% lower than that in 1.2–1.4 m layer, while root length density in 1.2–1.4 m layer was only 30–40% lower than that in 1.0–1.2 m layer (Figure 3A, B). At anthesis, the root length density in 1.2–1.4 m layer ranged from 9 to 12 km m^{-3}, but only ranged from 0 to 4 km m^{-3} below 1.4 m (Figure 3B). At late grain filling, root length density also significantly decreased when soil depth was lower than 1.4 m (data not shown). The root length density data agreed to the available soil water in Figure 1 that the changes of available soil water below 1.4 m were very small. The limitation of root growth and water extraction below 1.4 m profile was due to a caliche layer (45% $CaCO_3$) in Pullman clay soil at about 1.4 m profile. Lower water use below 1.4 m in corn has been reported previously for the same soil (Howell et al., 1998; Musick and Dusek, 1980b). Therefore, the water extraction was significantly limited by root density and more than 40% available soil water below 1.4 m remained at late grain filling stage in treatments T-1, T-2 and T-3. Although Winter and Musick (1993) observed that the soil water extraction at anthesis by

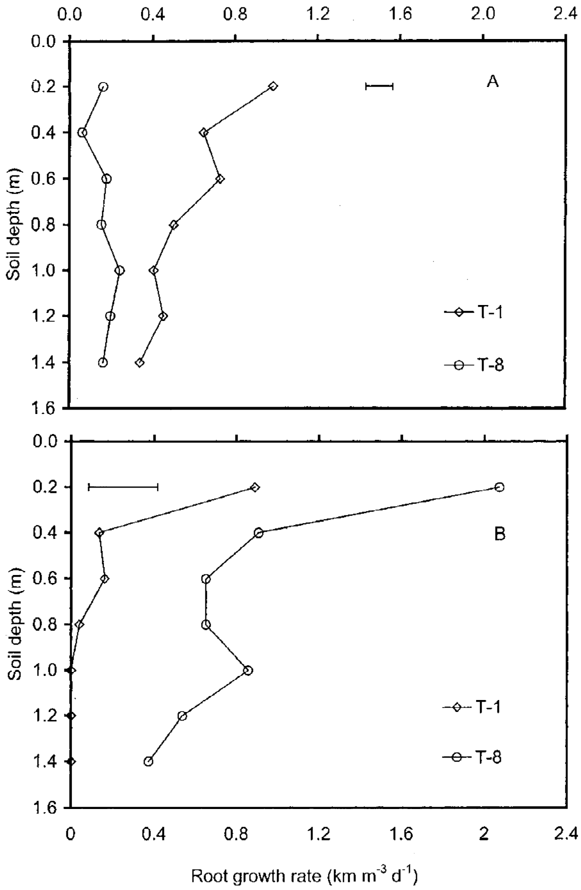

Figure 4. Mean root growth rate over the soil profile between floral initiation and booting (A) and between booting and anthesis (B) in rainfed (T-1) and adequate irrigation treatment (T-8). The horizontal bar represented the LSD at level of 0.05.

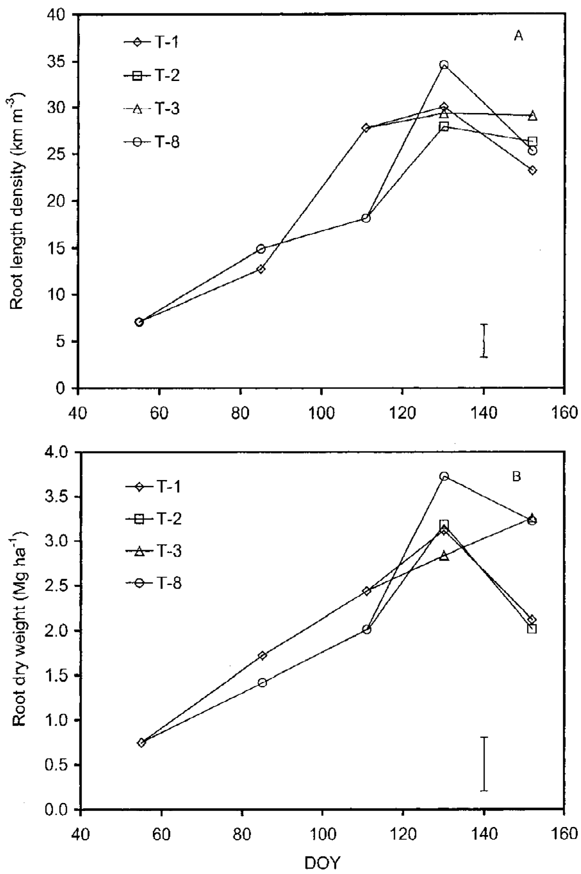

Figure 5. Seasonal changes of average root length density (A) and total root dry weight (B) over 0–1.4 m profile in rainfed (T-1), two one-irrigation treatments (T-2 and T-3), and adequate irrigation treatment (T-8). Vertical bar represented the LSD at level of 0.05.

winter wheat in early (Mid-August) and normal (early October) planting dates occurred as deep as 2.4 m, they did not measure root growth in their study. We also found that soil water extraction was as deep as 2.4 m in rainfed plot of this study. However, the water uptake from deeper soil profile (>1.4 m) would be difficult with a limiting root growth. Barraclough et al. (1989) and Meyers et al. (1990) both reported that water uptake from lower soil profile was limited by root density in wheat.

There were no significant differences in rooting depth among treatments ($P > 0.10$). However, irrigation significantly affected the rooting pattern. At booting, root length density in rainfed plots (T-1) was significantly higher than that in irrigated plots (T-8) ($P < 0.01$) over the 0–1.4 m profile (Figure 3A). At anthesis, the T-8 had higher root length density than T-1 ($P < 0.05$) (Figure 3B). From floral initiation to booting, root growth rate in T-1 was significantly ($P < 0.01$) higher than that in T-8 (Figure 4A). Previous studies also showed that soil drying at early stage stimulated root growth, particularly the root growth in the deeper soil profile (Asseng et al., 1998; Meyer et al., 1990; Zhang et al., 1998). Between booting and anthesis, however, root growth rate of T-1 was significantly reduced and was lower than that in T-8 (Figure 4B). The reduction of root growth rate of rainfed crops from booting to anthesis was related to low soil available water. Robertson et al. (1993) showed that sorghum root length density increased as available soil water decreased from 100% to near 30%, and then significantly decreased as available soil water was below 20%.

The seasonal changes of root length density averaged over 0–1.4 m soil profile are shown in Figure 5A for T-1, T-2, T-3 and T-8. Rapid root growth oc-

Table 3. Root length density and root dry weight average over 1.4 m profile at late grain filling, seasonal evapotranspiration (ET), grain yield, final biomass, harvest index, and water-use efficiency calculated by yield (WUE) and biomass (WUEbm) in winter wheat under different irrigation conditions

TRT	Root length density km m^{-3}	Root dry weight Mg ha^{-1}	Seasonal ET mm	Grain yield Mg ha^{-1}	Biomass	Harvest index	WUE kg ha^{-1} mm^{-1}	WUEbm
T-1	23.2abc	2.1c	414e	3.2e	10.6e	0.306c	7.8c	25.6a
T-2	26.3ab	2.0c	498d	4.6d	13.4c	0.346ab	9.3a	26.9a
T-3	29.1a	3.3a	494d	4.7d	13.9c	0.341b	9.6a	28.2a
T-4	22.3bc	2.5bc	496d	4.6d	12.8cd	0.357ab	9.2ab	25.8a
T-5	19.8c	2.3c	427e	3.6e	12.0d	0.302c	8.4bc	28.0a
T-6	22.8bc	3.2a	604b	6.0b	15.9b	0.377a	9.9a	26.4a
T-7	27.7ab	2.9ab	547c	5.4c	15.2b	0.359ab	9.9a	27.8a
T-8	25.3abc	3.2a	686a	6.7a	18.1a	0.370ab	9.7a	26.4a

In each column, different letters represented the significant difference at level of 0.05 based on the LSD test.

curred from floral initiation to anthesis and the root length density reached to maximum at anthesis. Root length density decreased significantly after anthesis in T-1 and T-8. Irrigation had a significant effect on mean root length density. At booting (DOY 111), crops in T-1 had higher root length density ($P < 0.05$) than those in T-8. At anthesis, however, the difference in root length density between T-8 and the other treatments was only significant at level of $P = 0.10$, and T-8 tended to had higher root length density. At late grain filling, root length density in T-2, T-3 and T-7 was higher than that in T-5, while there were no significant differences in root length density among T-1, T-4, T-6 and T-8 (Figure 5A, Table 3).

The patterns of total root dry weight over the 0–1.4 m profile were similar to root length density (Figure 5B). There were no significant differences in root dry weight among treatments from floral initiation to booting ($P > 0.10$). Differences in root dry weight among treatments were observed at anthesis and late grain filling. At anthesis, crops in T-8 had higher root dry weight than those in other treatments (T-1 to T-3). At late grain filling, root dry weight in T-3, T-6 and T-8 was significantly higher than that in T-1, T-2, T-4 and T-5 (Table 3).

The mean root water uptake rate in the rainfed treatment (T-1) from floral initiation to booting and from booting to anthesis is shown in Figure 6. From floral initiation to booting, root water uptake rate ranged from 63 to 167 mm^3 m^{-1} d^{-1} over 0–1.4 m profile. The maximum water uptake rate occurred between 0.4 and 0.8 m. The higher root water uptake rate of T-1 over 0–1.0 m profile from floral initiation

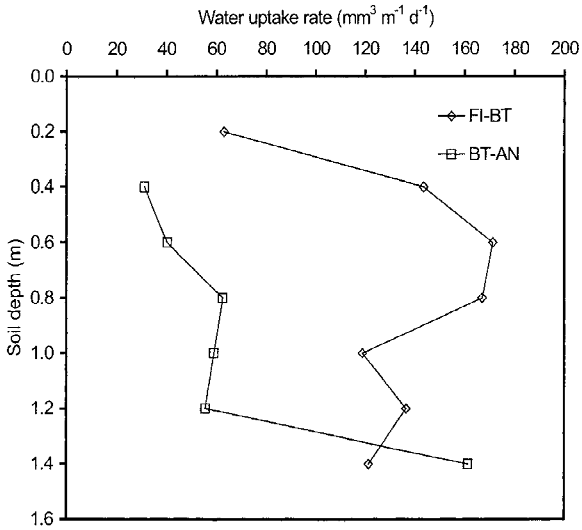

Figure 6. Mean root water uptake rate from floral initiation to booting (FI-BT) and from booting to anthesis (BT-AN) in rainfed plots over 0–1.4 m soil profile.

to booting may be related to the rapid root growth during this period. Asseng et al. (1998) and Meyer et al. (1990) both showed that maximum water uptake mostly occurred at or shortly after the time of maximum increase in root length density. The water uptake in T-1 significantly decreased from booting to anthesis over 0–1.2 m profile and ranged from 31 to 63 mm^3 m^{-1} d^{-1}. Root water uptake rate further decreased to less than 45 mm^3 m^{-1} d^{-1} in T-1 over 0–1.0 m profile during grain filling (Figure 7). The water uptake in the irrigated treatments (T-2, T-3 and T-8) was significantly higher than that in T-1 ($P < 0.05$) over

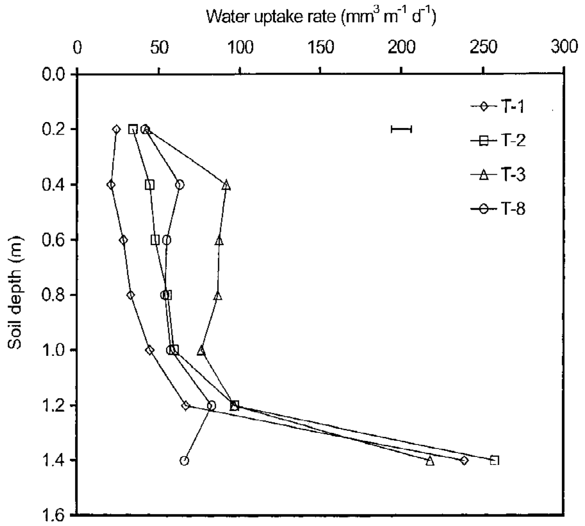

Figure 7. Mean root water uptake rate during grain filling in rainfed (T-1), two one-irrigation treatments (T-2 and T-3), and adequate irrigation treatment (T-8). The horizontal bar represented the LSD at level of 0.05.

0–1.2 m profile, and the water uptake in T-3 was the highest among the four treatments during grain filling (Figure 7). The root water uptake rate at 1.2–1.4 m layer was much higher ($>$160 mm^3 m^{-1} d^{-1}) than other soil layers ($<$100 mm^3 m^{-1} d^{-1}) for T-1, T-2 and T-3 from booting to late grain filling (Figures 6 and 7), probably due to a lower root length density but large changes in soil water content in 1.2–1.4 m layer. The water uptake values in soil layer deeper than 1.4 m were unrealistically high where the root length density values were very small (data not shown).

The significant reduction in root water uptake in rainfed treatment from booting to late grain filling was associated with low available soil water. Previous studies in wheat and sorghum both showed that root water uptake rate decreased linearly as available soil water decreased (Meyer et al., 1990; Robertson et al., 1993). During grain filling, the higher root water uptake in irrigated treatments (T-3, T-2 and T-8) than that in T-1 could be related to more depletion in soil water content between anthesis and late grain filling.

Seasonal evapotranspiration, grain yield, harvest index and water-use efficiency

Among the different treatments, rainfed plots had the lowest seasonal evapotranspiration, grain yield, harvest index and water-use efficiency in grain yield (WUE). Irrigation from jointing to anthesis significantly increased evapotranspiration, grain yield, harvest index and WUE (Table 3). The single irrigation at grain filling (2 weeks after anthesis, T-5) did not have higher evapotranspiration, yield, harvest index and WUE than rainfed. For the other three single irrigation treatments (T-2, T-3 and T-4), evapotranspiration increased 20%, and grain yield increased 41 – 46% as compared to rainfed. For the two-irrigation treatments, irrigation at jointing and anthesis (T-6) increased ET 46% and grain yield 85%, while irrigation at booting and grain filling (T-7) increased ET 32% and grain yield 67%. For the three-irrigation treatment (T-8), ET (686 mm) and grain yield (6.7 Mg ha^{-1}) were the highest and increased 165% and 209% as compared to the rainfed (T-1). Although grain yield increased as irrigation frequency increased, the WUE did not increase as irrigation frequency increased. For example, grain yield in T-2, T-3 and T-4 was 30% lower than that in T-8, and grain yield in T-6 and T-7 was 10–20% lower than that in T-8. However, there were no significant differences ($P > 0.20$) in WUE among these irrigation treatments. There were no significant differences ($P > 0.16$) in water-use efficiency in biomass (WUEbm) among all treatments (Table 3).

Although crops that received irrigation from jointing to anthesis significantly had higher grain yield and WUE than rainfed, there were no significant differences in rooting depth between rainfed and the irrigated crops. The difference between rainfed and irrigated crops in root length density was related to developmental stage. The rainfed treatment had greater root length density than irrigated treatment at booting, but there was no significant difference in root length density between rainfed and some irrigated treatments at late grain filling (Table 3). Therefore, the increased grain yield and WUE in irrigated treatments were not contributed by rooting depth or root length density in this study. Entz et al. (1992) and Hafid et al. (1998) shwed similar results that the higher WUE was not related to root length density. Both studies found that higher shoot dry weight contributed higher WUE (Entz et al., 1992; Hafid et al., 1998). In this study, the increased shoot dry weight in irrigated crops did not directly contribute to higher WUE since irrigation had no effect on WUEbm. Instead, the increased WUE in irrigated treatments was contributed by higher harvest index. The low harvest index in rainfed and the one-irrigation received at middle grain filling was due to the reduction of both seeds per square meter and seed weight (data not shown). In addition, higher root water uptake rate during grain filling also could contribute to higher WUE in irrigated crops.

The grain yield (3.2 Mg ha^{-1}) and WUE (7.8 kg ha^{-1} mm^{-1}) in rainfed treatment of this study were much higher than the rainfed yield (1.2–1.6 Mg ha^{-1}) and WUE (3.7–4.3 kg ha^{-1} mm^{-1}) in the same growing season and same soil under a 3-year wheat-sorghum-fallow rotation system (Jones and Popham, 1997). Comparing the seasonal evapotranspiration in two studies, rainfed crops in this study used 52 mm more water than those in Jones and Popham (1997), indicating that the root system in rainfed crops in this study was larger or deeper than that in Jones and Popham (1997). The relatively deep root system in this study was due to higher available soil water at early developmental stage. The deep root system at early developmental stage in rainfed treatment could allow the delay of irrigation at anthesis if only one irrigation is permitted. However, based on the precipitation distribution, precipitation at late stage (May–June) is more likely. Therefore, irrigation at early stage (e.g., jointing to booting) is more likely to maintain higher yield for winter wheat in this environment (Eck, 1988).

Conclusions

Low available soil water decreased from booting to late grain filling resulted in the lowest shoot dry weight, evapotranspiration, grain yield, harvest index and WUE in rainfed crops. Irrigation from jointing to anthesis increased shoot growth, evapotranspiration, grain yield, harvest index and WUE. Irrigation had no effect on water-use efficiency for biomass. For the deficit-irrigation treatments, shoot dry weight was related to frequency and timing of irrigation application. Crops that received irrigation at jointing and booting had higher shoot dry weight than those received irrigation at anthesis and middle grain filling. Available soil water levels did not affect rooting depth because of a relatively deep root system in rainfed crops. However, available soil water significantly affected rooting pattern. Soil drying from floral initiation to booting promoted root growth, but decreased root growth from booting to late grain filling. Root water uptake rate decreased as available soil water decreased. During grain filling, root water uptake in irrigated crops was higher than that in the rainfed. The root growth and water uptake below 1.4 m were limited by a caliche (45% $CaCO_3$) layer at about 1.4 m profile. Due to a relatively deep root system in the rainfed treatment, the higher grain yield and WUE in irrigated crops than rainfed were not contributed by rooting depth or root length density, but increased harvest index, and higher root water uptake during grain filling. The deep root system in rainfed treatment demonstrated the importance of higher soil water content at early spring growing season to rainfed grain yield and water-use efficiency.

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